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The influence of rainfall on road accidents in urban areas: A weather radar approach

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ABSTRACT

This paper presents a novel and rigorous approach to the analysis of the impact of rainfall on road traffic accidents in urban areas. It is argued that previous approaches to rainfall quantification for accident analysis, primarily using a representative surface meteorological station to represent an urban area, may not give an accurate record of the conditions across the city in question. Using an innovative city-wide weather radar approach to rainfall quantification and matched-pairs analysis, road accidents in the UK cities of Manchester and Greater London are examined over a 3-year baseline period (2008–2011). A comparative study is made over the same period used a traditional station-based approach. The resulting relative accident rates demonstrate divergence between the two cities and the two approaches. Although the stricter criteria for a rain event under the weather radar approach gives an increased RAR in Manchester, the RAR observed under these conditions decreases in Greater London. Reasons for the variation in RAR are explored and include traffic volume and speed, other coincident weather conditions and driver behaviour, in accordance with Elvik's (2006) laws of accident causation. It is argued that the approach described in this study offers significant improvements to the analysis of current weather-related accidents by giving a more representative measure of rainfall in urban areas.

Introduction

Rainfall is consistently cited as the weather type responsible for the greatest number of weather-related accidents (Edwards 1999; Qiu and Nixon 2008). Rain causes accidents through a combination of several physical effects that degrade the driving environment, including a loss of friction between the tyre and road and impaired visibility through rain on the windshield and spray from other vehicles. It is this combination of negative factors (Fridstrom et al., 1995) and the resulting strain on cognitive capacity (Elvik 2006) that leads to increased accident rates.

Previous studies investigating the influence of rainfall on road accidents have concentrated on cities and urban areas (e.g. Andrey et al. 2003; Hambly et al. 2013). This focus is justifiable due to the relative and increasing importance of cities as the world becomes increasingly urbanised. Over 50% of the world's population now live in urban areas, a figure which has been projected to rise to 67% worldwide by 2050 and 86% in more developed regions (United Nations, 2012). As a result there has been a growing research agenda around studies on urban areas across the sciences, including a particular focus on cities by the climate change impact community (e.g. Hall et al. 2010).

Although improved vehicle design and driver training have led to reductions in weather-related accident rates across the developed world in recent decades (Qiu and Nixon 2008; Andrey 2010), the growing urbanisation and projected increase in extreme weather events (in particular rainfall: IPCC, 2007) makes an effective approach for rain-related accident analysis essential. However, as will become clear there are currently several key weaknesses in the way that current city-based accident analysis is carried out. The following section reviews the current literature on the effect of rainfall on road accidents.

Rainfall and road accidents in cities

The effect of rainfall is usually expressed through relative accidents rates (RARs), the ratio of accidents recorded during a precipitation event to those during normal conditions. The matched pairs approach is commonly employed to determine RARs, and works on the basis that within a given area, the accidents observed (usually through police reports) during a period experiencing rain can be compared with a corresponding dry period. This is usually achieved by comparing a period exactly a week preceding or following the event, with the assumption being that other factors such as volume of traffic, driver demographic and light conditions will be broadly similar. Table 1 displays the relative accident rates obtained from several city-based studies, in these cases varying between 1.2 and 2.0.

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Table 1
Relative accident rates from previous studies.

Study	Location	Period	Relative accident rate
Smith (1982)	Glasgow, Scotland	1978–1979	1.2–1.3
Andrey and Olley (1990)	Edmonton, Cananda	1983	1.3–1.9
Andrey and Yagar (1993)	Alberta, Canada	1979–1983	1.7
Changnon (1996)	Chicago, USA	1977–1979	2.0 (30% more accidents in densely populated areas)
Andrey et al. (2003)	Various mid-sized Canadian cities	1995–1998	1.75
Keay and Simmonds (2006)	Greater Melbourne, Australia	1987–2002	1.61–1.67
Hambly et al. (2013)	Greater Vancouver, Canada	2003–2007	1.13–1.55

The variation in RAR in previous studies is partly attributable to the particularities of the cities or regions in question and the historical period of the study. Broadly speaking, more recent studies show lower RARs due to aforementioned safety and driver training improvements (Andrey 2010). Differences between locations are attributed to factors such as road design, lighting, speed limits, driver training and frequency of exposure to rainfall (Fridstrom et al., 1995; Elvik 2006). It has also been shown that greater rainfall intensities lead to higher RARs and injury rates (e.g. Hambly et al. 2013). However, there are several longstanding methodological difficulties that call into question the validity of RARs obtained in urban areas and make direct comparison between studies extremely difficult.

One of the biggest problems in urban studies is the lack of representative meteorological station observations at suitable spatial and temporal resolutions. Urban areas have distinct microclimatic features attributable to their material and topographical properties as well as associated human activities such as transport and industry. This is most well known through the 'urban heat island' effect where urban areas have higher temperatures than surrounding non-urbanised areas (Oke, 1973). However, urban activity also leads to local effects on precipitation such as rainfall suppression. Aerosols in urban areas which have hygroscopic properties allow water in the atmosphere to be carried in a greater number of smaller droplets which do not precipitate out of the atmosphere (Rosenfeld 2000). Although the growing importance of instrumentation of urban areas has been noted (Oke 2006), efforts to implement urban networks have had mixed success (Muller et al., 2013a).

The relative absence of stations, largely attributable to the failure of such sites to meet the World Meteorological Organisation's guidelines on meteorological instruments and methods (WMO, 2008; Muller et al., 2013b), makes obtaining valid RARs difficult. Airports often provide the closest observations, but as Andrey et al. (2003) notes these can be as far as 35 km away from the city in question. Even where a city-centre station is available such as the one used by Keay and Symonds (2006) in Melbourne, the lack of coverage from a comprehensive city-wide network means the representativeness of the rainfall situation at any given time is questionable. The station in question is used to represent an area of almost 9000 km^2, within which large differences in rainfall timing and amount will be expected. It is clear that a more representative measure of rainfall would be beneficial for the formation of realistic RARs.

A further methodological issue is that RARs have consistently been shown to be highly sensitive to the temporal unit of study (Qiu and Nixon 2008). For example, although Smith (1982) found accident rates increased by 20–30% on days where rain is observed, it is conceded that this was likely to underestimate the precipitation impact, given that the days categorised as 'rainy' will contain periods of dry weather. In contrast, Andrey and Yagar (1993) used a variety of smaller temporal units and hourly rainfall data to capture more accurately the duration of rain events. Although the temporal distribution of precipitation within these periods is likely to vary, it is still clearly a far more accurate method than using daily data which include large variations in both rain and traffic volumes. However, the authors of this study concede that varying the temporal unit of analysis may allow any short-term behavioural change due to exposure to an extended rain event to influence the results.

These behavioural problems associated with the temporal unit of analysis are highlighted by Eisenberg (2004) who investigated the mixed effects of precipitation on traffic crashes in the USA. Monthly and daily units were used, with rainfall being evaluated by total precipitation. A negative and statistically significant relationship between monthly precipitation and monthly fatal crashes is reported, yet the opposite was found when a daily temporal unit analysis was employed. When investigated in further detail it was found that the increase in accident rate for a given rain day was three times greater if 20 days had passed since the last recorded precipitation compared with those events which experienced rain in the previous 2 days. This relates to a study by of Changnon (1996) in Chicago, who found that rain days during dry months produced more accidents and injuries than during normal or wet months.

These findings clearly indicate that short-term behavioural change is taking place, as described by Elvik's 'laws of accident causation' (2006). Increased exposure to hazardous conditions allows drivers more opportunities to learn to cope in these conditions, hence increasing personal and group resilience. It must also be noted that physical conditions are also altered by the frequency of rainfall with long dry spells leading to polished and oily road surfaces that become hazardous when wet. These behavioural and physical observations are also important in the context of climate change, as any change in the frequency of rain events will alter drivers' abilities to cope in these conditions (in both the short and long-term) and affect the physical driving conditions. Hence, it is important to remember that any obtained RAR will be influenced by the temporal unit of study and the particular patterns of rainfall exposure associated with a given city.

Overview of approach

This study attempts to address the two main methodological issues highlighted in the literature review; the spatial and temporal representativeness of meteorological data in city-based accident analysis. Matched pairs analysis is performed on two large UK cities UK Meteorological (Met) Office NIMROD weather radar images directly over the urban areas to give a more representative measure of rainfall than station-based approaches. These high spatial (5 km) and temporal resolution images (1 h) have previously been used to study the effect of rain of road traffic speeds (Hooper et al. 2012). Although this study considers UK cities, discussion is made on how the approach and methods can be applied to any urban area with available weather radar data, with suggestions on how other unconventional data could be used in areas without radar coverage.

Locations and data

Accident data

STATS19 accident data (DfT 2011) were obtained for the three year period of 2008–2011, a time period comparable to other studies and one that limits the influence of changes in vehicle design, driver behaviour and climate. Forms are recorded at the scene of every road traffic accident in the UK to which a representative of the police has attended and include information on the location (longitude and latitude), date, time and weather condition. For the purposes of this study, the time given on the STATS19 accident report is taken as the time at which the accident occurred, although it is accepted that there will be a lag between the accident and the report (Edwards 1999). Misreporting of weather or road surface conditions is also a common error, where police may report the weather condition present at the time of the report and not the time of the accident. The results of this matched pairs analysis are then compared to results achieved through a traditional meteorological station-based approach. By using a relatively short temporal unit of study (a 3 h rain event was used) and strict criteria for a rain event it was hoped that the effect of temporal variations in rainfall would be limited. However, in this study the weather field is only used for the identification of locations and not to inform the matched pairs.

Selection of locations

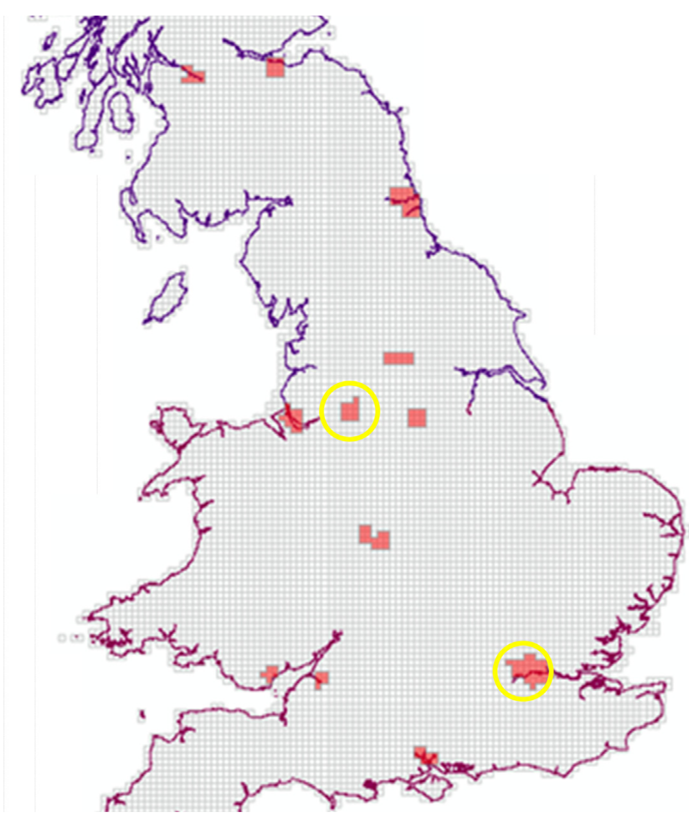
Two criteria were set for selection of urban areas: (i) that they accounted for a large share of the national urban road traffic accident total (ii) that they displayed a difference in climatology that could be used to examine potential behavioural effects of exposure. A Geographical Information System (GIS) was used to delineate the urban area of 12 UK cities at a 5 km grid square resolution (Fig. 1). Totals for accidents with rain recorded as a meteorological parameter were ascertained from STATS19 accident data. London and Manchester were chosen in order to provide a large number of records as well as differences in annual rainfall. Although Birmingham was considered for analysis, gaps in the meteorological station data set prevented its inclusion.

Meteorological data

Hourly NIMROD weather radar images were obtained at a 5 km Cartesian grid scale for the period of 2008–2011. The images are derived from data captured by a network of 'C-band' rainfall radar stations which is processed by the UK Meteorological (Met) Office NIMROD system. Scans at various elevations at each site are conducted giving an estimate of rainfall at the ground. The validity of these estimates is checked routinely using rain gauges at ground level. The radar coverage area, based on the urban area of the cities is given in Figs. 2 and 3. Conventional meteorological station data for rainfall were obtained from the Met Office's MIDAS network of surface meteorological stations (accessed through the British Atmospheric Data Centre). Stations were chosen to represent the urban areas of Manchester and Greater London: 'Hulme Library' for Manchester and 'St James's Park' for Greater London Figs. 2 and 3. Rainfall for these stations is recorded at hourly intervals.

Methodology

To address the problems associated with large temporal units of analysis, such as the variability of precipitation intensity, whilst still allowing for a large number of accident records, a rain event period of 3 h was deemed appropriate, and has previously been used in a study by Keay and Simmonds (2006). Criteria were set to ensure that each selected rain event covered the majority of the urban areas. For the purposes of this study a 3 h period is considered a rain event if in excess of 70% of grid squares receives between 0.5 and 4 mm/hr for all 3 h (approximately corresponding to



Area (City)	2010 'Rain' Accidents
London	1833
Birmingham	473
Newcastle	352
Manchester	286
Glasgow	248
Liverpool	237
Leeds	217
Sheffield	184
Edinburgh	145
Southampton	127
Bristol	107
Cardiff	80

Fig. 1. Map showing the 12 considered study location collection areas and corresponding table showing number of accidents recorded under rain conditions in 2010 (selected cities in red). (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

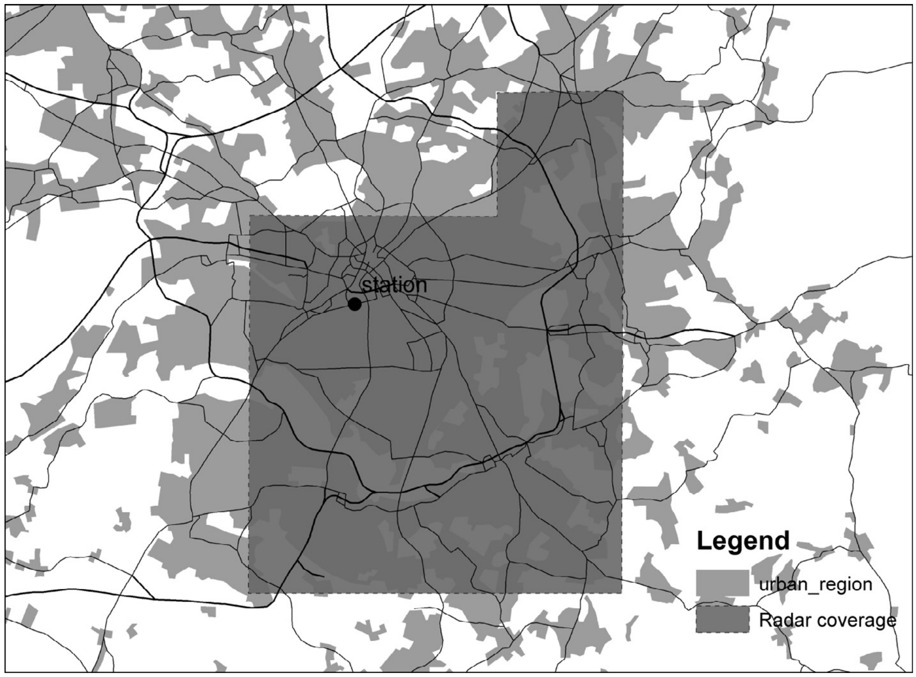


Fig. 2. Map showing Greater Manchester urban area, meteorological station location and radar coverage (5 km grid scale).

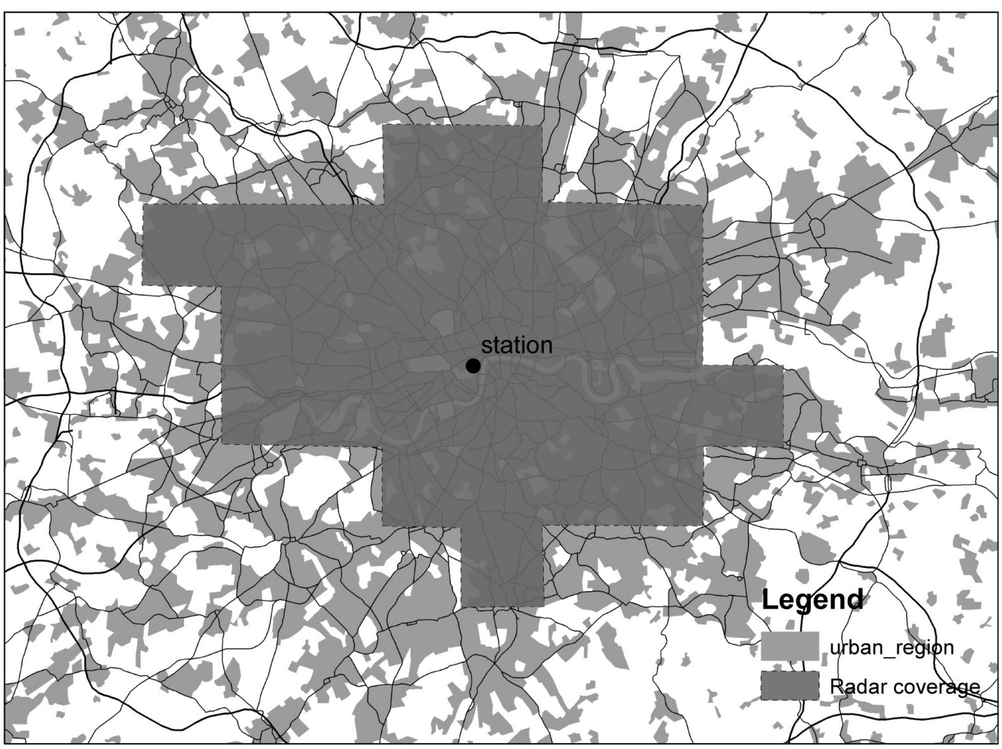


Fig. 3. Map showing Greater London urban area, meteorological station location and radar coverage (5 km grid scale).

the American Meteorological Society's (2012) light-moderate rain categories). Fig. 4 shows an example of this rain event identification process for Manchester. Dry events are classified as 3 h periods where no precipitation is captured by the radar images.

Matched pairs were selected if a suitable dry day was available exactly one week before or after a rain event. Matched pairs including a public holiday or weekend were unusable, as traffic volume and road user demographic were likely to differ considerably. Additionally the ability to change travel plans in the presence of weather is likely to be greater on these days. The matched pairs were selected from weekdays between the hours of 7:00 and 20:00. The timings were chosen to reduce the influence of low traffic volumes later at night, while still providing a large number of potential match pairs. However, it must be mentioned that this period will still have temporal variations in the ability to reduce exposure. The number of accidents that occurred during the 3 h period for both the rain and non-rain events of the matched pair was ascertained using ArcGIS. A spatial join was created between

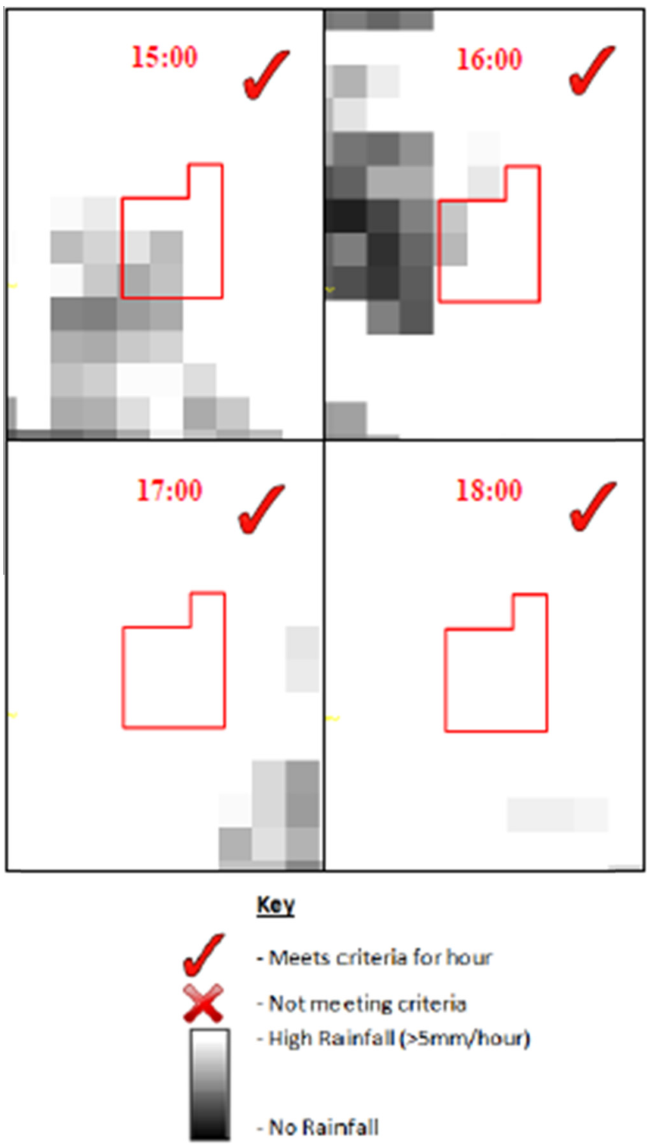


Fig. 4. Nimrod analysis for Manchester on 2nd November 2010.

the city shape file and the *X–Y* point data imported from the STATS 19 records for the 3 h in question based on the time recorded in the police accident reports. By finding an accident total for both rain and non-rain events over the study period for each of the three cities it was possible to derive RARs. This was repeated using station data, with the same criteria for rainfall amount. In both cases only one rain event was selected per day, that being the first 3-h rain event that occurred.

Results

Conventional station-based matched pairs analysis

The RARs for the study cities using the rainfall radar and station approaches are given in Table 2. The RAR is greater than unity in both cities using the conventional station-based approach suggesting that rainfall consistently represents a driving hazard. For Manchester, the relative accident rate of 1.5 implies that proportionally 1.5 accidents occur during rain events for every 1 accident during an equivalent dry spell. London has a lower RAR of 1.18. By using these RARs the number of accidents over the 3 year period attributed to sustained rained events can be estimated (Table 2).

The relative accident rates obtained though the station-based approach are comparable with those in the literature (Table 1). A parallel can be drawn with the Melbourne study by Keay and Simmonds (2006) which also used 3-h temporal unit and consistently produced a larger RAR than a comparative analysis using a daily categorisation of rain events. The closest comparable RAR in the literature comes from Smith's (1982) study in Glasgow. It is conceivable that the behaviour and attitude of drivers (partly determined by frequency of exposure to rainfall), road design and driver training will be similar to that of the cities investigated in this study. However, both the age of the study and the daily unit of analysis make direct comparison difficult.

A potential reason for the low RAR in London is the larger number of overall road accidents due to the size of the city. This is likely to reduce the influence of outlying matched pairs associated with the random variation in accident numbers common in small spatial and temporal sample sizes. It must also be noted that London is the largest and busiest city with the lowest average speeds in the study. This would agree with the results of Edwards (1998) who found the severity of accidents were lower in urban areas where average speeds are lower (although better road lighting is also stated as a factor).

The observation that Manchester has both the highest annual rainfall and RAR and London the lowest annual rainfall and RAR (during rain events) appears to contradict the Elvik's behavioural laws (2006). However, there are potential reasons why Elvik's laws may not hold true in this study. Firstly, the UK has a wet climate and experiences a large proportion of rain days (Manchester experiences 141 rain days a year), making this a common driving condition. The increase in RAR in Elvik's example of snow and ice covered roads in Sweden only arises at relatively low exposure levels. It may be true that a point exists at which a developing competency at managing a hazard is impinged by complacency. The concept that exposure increases the ability of a driver to manage a hazard necessitates that rain is seen and treated as a hazard by drivers. Its prevalence in the UK may mean this is not in fact the case. Secondly, if Elvik's laws are to be considered for this study it must be assumed that motorists driving in the rain events have been regularly subject that that city's hazard exposure level. This cannot be said with any certainty.

Radar-based matched pairs analysis

In comparison with the results from the traditional station-based approach, the RARs obtained from the weather-radar approach diverge considerably. It must be noted that for both cities the number of matched pairs reduces when using the weather radar data (Table 2). The number of viable matched pairs reduces from 45 to 32 in Manchester and from 26 to 15 in Greater London. This is to be expected as the criteria for rainfall amount must be met for the majority of grid squares in the cities over the 3-h period, as opposed to a single site in the weather station approach.

In Manchester the RAR increases from 1.5 under the station-based approach to 1.82 when using weather-radar data. This would appear to be logical considering characteristics of the two approaches. Although the stations question is situated in central Manchester and hence more representative than those used in several other studies, it will only give the meteorological conditions at one site, with the potential for large parts of the city to experience concurrent dry-periods. If rainfall increases RARs, then it should be expected that a rain event that is known to cover the majority of the urban area should produce higher RARs.

However, the result from Greater London shows a reduction in RAR from 1.18 to 0.97, indicating a marginal reduction of accidents during rainfall. Although this number is close to the already marginal figure given by the station approach, the lower RAR is

Table 2
Summary of matched pair accident counts, relative accident rates and estimated accident attributable to rainfall.

Location	Number of matched pairs	Accident count (rain/non-rainfall)	RAR	Accident attributed to rainfall
Station rainfall				
Manchester	45	111/74	1.5	37
London	32	393/334	1.18	59
Radar rainfall				
Manchester	26	80/44	1.82	36
London	15	176/181	0.97	−5

unexpected given the hypothesis outlined in this paper. This result may be due to the relatively small number of matched pairs used in the ensemble, exacerbated by the strict criteria given for the radar approach. However, this result may be explained through the previously mentioned characteristics of urban road travel in London, which is slower and more congested than in Manchester and may prevent accidents associated with loss of control and visibility at high speeds. It may also be the case that the greater provision of public transport in London may facilitate modal shift in periods of inclement weather.

Discussion

Accident relationships

The use of weather radar images for city-based accident analysis has been demonstrated to be an alternative to conventional data, and offers considerable improvements to the accuracy and representativeness of rainfall used to determine matched pairs. As with all road accident analysis studies the quality of the findings are somewhat limited by the reliability of the data. The previously reported lag between the time of an accident and the time of the police report (Edwards 1999) will have undoubtedly affected this study. Consideration was given to the idea of correcting the time by a factor to account for this error. However, without knowing this average attendance time any compensatory attempts would be speculative and arbitrary. It must be remembered that any biases for or against reporting accidents under different conditions are implicit in the matched pairs approach. For example, it is conceivable that drivers will be less likely to wait for police to arrive after a minor incident if the weather is inclement. This is the same for other changes such as the decision of drivers to postpone or cancel their journeys during periods of rain, which may have the effect of reducing exposure during these periods.

Another factor which is very difficult to normalise for is other coincident weather conditions and the effect they might have on accident rate. Ice, for example, is seen to have a large effect (Elvik 2006). It is possible that further filtering could be achieved with the use of observations from surface stations. The study could also disaggregate for time of day and season, as these have been shown to influence RAR (Changnon 1996; Keay and Simmonds 2004).

The spatial and temporal criteria set for a rain event in this study limited the number of matched pairs compared to a station approach. As a result all accident types (property damage only, minor injury, serious injury) were included to obtain as large an accident count as possible. It also dictated the use of a single category for rainfall amount. Although the aim of this study was to compare a conventional and alternative approach under identical criteria rather than investigate the impact of rainfall intensities on RARs or injury rates, this would be possible using the weather radar approach. However, this would likely require a longer period of study than the 3 years used in this analysis.

Further application

In theory, this approach can be applied to any area with weather-radar coverage, which will include most developed countries. However, there are also emerging techniques that can be used to create similar precipitation estimates in areas without coverage. For example, Overeem et al. (2013) demonstrate that mobile-phone networks can be co-opted to create analogous data. As rainfall affects the way in which electromagnetic radiation travels through the air, by measuring the strength of the microwave signals that base stations use for communication it is possible to produce estimates of rainfall. The fact that mobile networks are most widespread in cities and that the past decade has seen a rapid growth in coverage in developing countries offers a potentially useful untapped source of data. This trend, twinned with existing weather radar coverage means that the approach described in this study can potentially be used for accident analysis in any urban area. Indeed, these data would be applicable to any investigation that requires high resolution rainfall data over an urban area.

The weather radar approach could form a useful component for climate change impact assessment in cities. The assessment of potential climate change impacts on transport is a field of research in its infancy, and it has been noted that significant work is required to develop quantitative assessment methods and frameworks (Koetse and Rietveld 2009; Jaroszweski et al., 2010). Among those studies that have attempted quantification there has been a focus on road transportation, particularly on the impact on weather-related accidents in cities (e.g. Andersson and Chapman, 2011; Hambly et al., 2013). However, the present-day RARs used to extrapolate the impact of climate change suffer from the same methodological problems associated with cities as mentioned previously. A move towards weather radar techniques would improve the accuracy of this component of the assessments and would benefit from using the same spatial grid scale as existing climate projection tools. For example the UKCP09 Weather Generator (Jones et al., 2009) could be used for city-based studies such as Hambly et al. (2013) or be used to project change over wider regions such as in Jaroszweski et al. (2013) study on road freight accidents in the UK.

Conclusion

This study demonstrates an alternative approach to weather-related accident analysis in cities and urban areas. Of the two cities studied, Manchester demonstrates the expected trend in a move away from a station-based approach to the use of weather radar images, with RARs increasing from 1.5 to 1.82. However, the result from London shows minor reduction in RAR under the radar-based approach. Although both station and radar RARs are marginal, and come from relatively small sample sizes, the results may indicate a differences in the nature of urban road travel in the cities based on both on traffic volume and speed, but also the behavioural responses of drivers in terms of modal shift and journey alterations.

It is argued that the approach described in this paper offers significant advantages over traditional station-based analyses, namely a better representation of rainfall over the urban area and finer spatial and temporal resolutions. Although this study is based on cities in the UK, the approach is applicable to any other urban area with comparable data, either from weather radar images or other unorthodox sources. The growth in urban populations along with the projected increase in extreme weather events due to climate change is likely to make weather an increasingly significant road accident hazard. The approach described in this paper is a potentially useful addition to future climate change impact assessments in these areas and may aid adaptation actions.

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References

The American Meteorological Society. 2012. Glossary of Meteorology: Rain, http://glossary.ametsoc.org/wiki/Rain (accessed 01/08/2013).

Andersson, A.K., Chapman, L., 2011. The impact of climate change on winter road maintenance and traffic accidents in West Midlands. UK. Accid Anal Prev 43 (1), 284–289. http://dx.doi.org/10.1016/j.aap.2010.08.025.

Andrey, J., Mills, B., Leahy, M., Suggett, J., 2003. Weather as a chronic hazard for road transportation in Canadian cities. Nat. Hazards 28 (2–3), 319–343. http://dx.doi.org/10.1023/a:1022934225431.

Andrey, J., Olley, R., 1990. Relationships between weather and road safety: past and future research directions. Climatological Bulletin 24 (3), 123–127.

Andrey, J., Yagar, S., 1993. A temporal analysis of rain related crash risk. Accident Anal. Preven. 25 (4), 465–472.

Andrey, J., 2010. Long-term trends in weather-related crash risks. J. Transp. Geogr. 18 (2), 247–258. http://dx.doi.org/10.1016/j.jtrangeo.2009.05.002.

Changnon, S.A., 1996. Effects of summer precipitation on urban transportation. Climatic Change 32 (4), 481–494.

DfT. 2011. STATS19 data access via ESDS access and preservation. UK Data Archive, Accessed November 2011.

Edwards, J.B., 1998. The relationship between road accident severity and recorded weather. Journal of Safety Research 29 (4), 249–262.

Edwards, J.B., 1999. The temporal distribution of road accidents in adverse weather. Meteorol Appl 6 (1), 59–68. http://dx.doi.org/10.1017/s1350482799001139.

Eisenberg, D., 2004. The mixed effects of precipitation on traffic crashes. Accid Anal Prev 36 (4), 637–647. http://dx.doi.org/10.1016/s0001-4575(03)00085-x.

Elvik, R., 2006. Laws of accident causation. Accid Anal Prev 38 (4), 742–747. http://dx.doi.org/10.1016/j.aap.2006.01.005.

Fridstrom, L., Ifver, J., Ingebrigtsen, S., Kulmala, R.Krosgsgard., Thomsen, L., 1995. Measuring the contribution of randomness, exposure, weather and daylight to the variation in road accident counts. Accident Analysis and Prevention 27 (1), 1–20.

Hall, J.W., Dawson, R.J., Barr, S.L., et al., 2010. City-scale integrated assessment of climate impacts, adaptation, and mitigation, Energy Efficient Cities: Assessment Tools and Benchmarking Practices, 63–83. World Bank, Washington DC, USA.

Hambly, D., Andrey, J., Mills, B., Fletcher, C., 2013. Projected implications of climate change for road safety in Greater Vancouver, Canada. Climatic Change 116 (3–4), 613–629. http://dx.doi.org/10.1007/s10584-012-0499-0.

Hooper, E., Chapman, L., Quinn, A., 2012. Investigating the impact of precipitation on vehicle speed on UK motorways. Meteorological Application, in press. http://dx.doi.org/10.1002/met.1348.

IPCC. 2007. In: Solomon, S. Qin, D. Manning, M. Chen, Z. Marquis, M. Averyt, K.B. Tignor, M. Miller, H;L. (Eds) Contribution of working group I to the forth assessment report of the IPCC, Cambridge University Press, Cambridge.

Jaroszweski, D., Chapman, L., Petts, J., 2010. Assessing the potential impact of climate change on transportation: the need for an interdisciplinary approach. J Transp Geogr 18 (2), 331–335. http://dx.doi.org/10.1016/j.jtrangeo.2009.07.005.

Jaroszweski, D., Chapman, L., Petts, J., 2013. Climate change and road freight safety: a multidisciplinary exploration. Climatic Change 120 (4), 785–799. http://dx.doi.org/10.1007/s10584-013-0836-y.

Jones, P.D., Kilsby, C.G., Harpham, C., Glenis, V., Burton, A., 2009. UK climate projections science report: projections of future daily climate for the UK from the Weather Generator. University of Newcastle, UK.

Keay, K., Simmonds, I., 2006. The association of rainfall and other weather variables with road traffic volume in Melbourne, Australia. Accident Analysis and Prevention 37, 109–124.

Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: An overview of empirical findings. Transport Res Part D-Transport Environ 14 (3), 205–221. http://dx.doi.org/10.1016/j.trd.2008.12.004.

Muller, C.L., Chapman, L., Young, D.T., Grimmond, C.S.B., Cai, X., 2013a. Sensors & the city: a review of urban climatological sensor networks. International Journal of Climatology 33 (7), 1585–1600. http://dx.doi.org/10.1002/joc.3678.

Muller, C.L., Chapman, L., Young, D.T., Grimmond, C.S.B., Cai, X., 2013b. Towards a standardised metadata protocol for urban meteorological networks. Bulletin of the American Meteorological Society 94 (8), 1161–1185. http://dx.doi.org/10.1175/BAMS-D-12-00096.1.

Oke, T.R., 1973. City size and urban heat island. Atmospheric Environment 7 (8), 769–779.

Oke, T.R., 2006. Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites. World Meteorological Organisation, Geneva, Switzerland.

Overeem, A., Leijnse, H., Uijlenhoet, R., 2013. Country-wide rainfall maps from cellular communication networks. Proceedings of the National Academy of Sciences of the United States of America. http://dx.doi.org/10.1073/pnas.1217961110.

Qiu, L., Nixon, W.A., 2008. Effects of Adverse Weather on Traffic Crashes Systematic Review and Meta-Analysis. Transp Res Record 2055, 139–146. http://dx.doi.org/10.3141/2055-16.

Rosenfeld, D., 2000. Suppression of rain and snow by urban and industrial air pollution. Science 287 (5459), 1793–1796.

Smith, K., 1982. How seasonal weather conditions influence road accidents in Glasgow. Scot Geog Mag 98, 103–114.

United Nations, 2012. World population prospects: the 2011 revision. USA, New York.

World Meteorological Organisation, 2008. Guide to Meteorological Instruments and Methods of Observation, Seventh Edition. Geneva, Switzerland.